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«Central Asian Academic Research Center» LLP is pleased to announce that "News of NAS RK. Series of Geology and Technical sciences" scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of Geology and Technical Sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

«Орталық Азия академиялық ғылыми орталығы» ЖШС «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

ТОО «Центрально-азиатский академический научный центр» сообщает, что научный журнал "Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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EVALUATION OF THE EFFICIENCY OF USING FLY ASH IN POLYMER COMPOSITE MATERIALS

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Abstract. The relevance of this study is determined by the need for rational utilization of industrial waste and the development of environmentally sustainable building materials for the conditions of Kazakhstan. Fly ash from Almaty Thermal Power Plant No. 2, bentonite clay from a local deposit, and wood flour obtained from furniture production residues were selected as mineral fillers for polymer composite materials. The purpose of this research is to evaluate the efficiency of using thermally modified bentonite and fly ash as complex fillers for the production of wood–polymer composites and to determine their influence on the physical and mechanical properties of the materials. The applied research methods included X-ray fluorescence, X-ray diffraction, and thermogravimetric analysis for phase and elemental characterization, optical and electron microscopy for studying morphology and dispersion, and mechanical tests performed according to ISO 62, ISO 178, and ISO 2039-1 standards. The use of fly ash, as a filler for polymer composites has shown positive results in improving their properties, reducing production costs, and solving environmental problems. The results showed that the addition of 20 % fly ash and 5 % thermally modified bentonite at 700 °C increased flexural strength to 20.9 MPa, hardness to 8.47 HB, and reduced water absorption to 0.45 %. These findings confirm the compatibility of mineral fillers with the polymer matrix and demonstrate their reinforcing effect. The scientific novelty of the research lies in establishing the correlation between the thermal modification temperature of bentonite, the change in dispersion of its mineral phase, and their combined effect on the strength properties of wood–polymer composites.

Keywords: fly ash, bentonite, thermal modification, wood–polymer composite, building materials

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ПОЛИМЕРЛІ КОМПОЗИТТІК МАТЕРИАЛДАРДАҒЫ ҰШҚЫН КҮЛДІ ПАЙДАЛАНУДЫҢ ТИІМДІЛІГІН БАҒАЛАУ

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Аннотация. Зерттеу жұмысының өзектілігі – өнеркәсіптік қалдықтарды қайта өңдеу және Қазақстан жағдайында экологиялық тұрғыдан орнықты құрылыс материалдарын жасау қажеттілігімен анықталады. Полимерлі композициялық материалдарға минералды толтырғыш ретінде Алматы қаласындағы №2 ЖЭО-ның ұшпа күлі мен жергілікті кен орнынан алынған бентонит сазы пайдаланылды. Зерттеудің мақсаты – термиялық модификацияланған бентонит пен ұшпа күлді күрделі толтырғыштардың құрамында пайдалану тиімділігін бағалау және олардың негізінде ағаш-полимерлі композициялық материалдар алу. Қолданылған зерттеу әдістеріне фазалық құрамын және элементтік құрамын анықтау үшін рентгендік флуоресценция, рентгендік дифракция және термогравиметриялық талдау; морфологиясы мен таралуын зерттеу үшін оптикалық және электрондық микроскопия; сондай-ақ ISO 62 стандартына сәйкес жүргізілген механикалық сынақтар кірді. ISO 178 және ISO 2039-1. Полимерлік композиттерді толтырғыш ретінде ұшқын күлін қолдану олардың қасиеттерін жақсартуда, өндіріс шығындарын азайтуда және экологиялық мәселелерді шешуде оң нәтижелер көрсетті. Алынған үлгілерге механикалық сынақтар жүргізілді. Нәтижесінде құрамында 20 % ұшпа күл және 5 % 700 °C температурада термиялық модификацияланған бентонит бар композицияның ию беріктігі 20,9 МПа-ға дейін артты, су сіңіргіштігі 0,45 %-ға дейін төмендеді және қаттылығы 8,47 HB деңгейіне жетті. Алынған нәтижелердің практикалық маңызы – жергілікті өндірістік қалдықтарды құрылыс және әрлеу салаларында қолдануға болатын экологиялық таза, арзандатылған полимерлі композициялық материалдар алу мүмкіндігін қамтамасыз етуінде. Зерттеудің ғылыми жаңалығы бентониттің термиялық модификациясы температурасы, минералдық фазаның дисперсиясының өзгеруі және олардың ағаш-полимерлі композиттердің беріктік сипаттамаларына бірлескен әсері арасындағы байланысты анықтауда.

Түйін сөздер: ұшпа күл, бентонит, термиялық модификация, ағаш-полимерлі композит, құрылыс материалдары

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ОЦЕНКА ЭФФЕКТИВНОСТИ ИСПОЛЬЗОВАНИЯ ЗОЛЫ УНОСА В ПОЛИМЕРНЫХ КОМПОЗИТНЫХ МАТЕРИАЛАХ

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Аннотация. Актуальность работы обусловлена необходимостью утилизации промышленных отходов и разработки экологически устойчивых строительных материалов в условиях Казахстана. В качестве минеральных наполнителей для полимерных композитов использованы зола уноса Алматинской ТЭЦ-2 и бентонитовая глина местного происхождения. Цель исследования — оценить эффективность применения термически модифицированного бентонита и золы уноса в составе комплексных наполнителей при получении древесно-полимерных композитов. Методы исследования включали рентгенофлуоресцентный, рентгенодифракционный и термогравиметрический анализы для определения фазового и элементного состава, оптическую и электронную микроскопию для изучения морфологии и дисперсности, а также механические испытания по стандартам ISO 62, ISO 178 и ISO 2039-1. Также исследованы компоненты, усиливающие структуру композита. Использование золы уноса в качестве минерального наполнителя показало положительное влияние на свойства композитов, снижение производственных затрат и решение ряда экологических проблем. Установлено, что введение 20 % золы уноса и 5 % бентонита, модифицированного при 700 °C, повышает прочность при изгибе до 20,9 МПа, снижает водопоглощение до 0,45 % и увеличивает твёрдость до 8,47 HB. Практическая значимость заключается в применении локальных промышленных отходов как функциональных наполнителей для получения недорогих и экологичных полимерных композиционных материалов, востребованных в строительстве и отделочных работах. Научная новизна состоит в установлении зависимости между температурой термомодификации бентонита, изменением дисперсности его минеральной фазы и их совместным влиянием на прочностные характеристики древесно-полимерных композитов.

Ключевые слова: зола уноса; бентонит; термическая модификация; древесно-полимерный композит; строительные материалы

Introduction. The use of fly ash in industry, particularly in the construction industry, is one of the strategic ways to solve the environmental problem of pollution and increase the depth of coal processing. This study investigated the possibility of comprehensive use of industrial waste, namely coal fly ash (FA) and bentonite from the Kazakh deposit, to obtain a dispersed filler for the production of wood-polymer composite (WPC) material. In countries that traditionally use coal combustion, various methods of using and disposing of FA are proposed, for example, for the production of cement-based building materials, thermal insulation, and heat-resistant materials, in which, according to researchers, FA contributes to better insulation characteristics (Sumio, et al., 2000; Xingbao et al, 2008; Łach et al 2016; Horiuchi et al 2005). In Kazakhstan, research is being conducted and projects are being planned for the utilization and processing of FA in road construction and for the production of silicate building materials (Muratov et al., 2023; Musina et al., 20206, Nurpeissova et al., 2023).

Bentonite and kaolin clays are used in polymer technology (Roy, 2024; Mapossa et al., 2024). To obtain a composite material with the desired properties, modifiers are used, which can be processing additives, additives or antioxidants, additives and fillers that improve the physical and mechanical properties of the final product. Kaolin with a particle size of up to 1 μm is used as a structuring additive for translucent polymers, and the finely dispersed fraction is used to fill LDPE, HDPE, LLDPE, and PVC. Kaolin can replace hydrophobic chalk. For use in filled polymers, kaolin is modified (Ibadullayev et al., 2021). Chemically and thermally modified kaolin is also used in cement mixtures. The optimal heating temperature for kaolin is 700 to 800 °C (Mejía et al., 2008). Kaolin and bentonite have a similar aluminosilicate composition, but differ in terms of particle dispersion and specific surface area: for kaolin, this is 50–150 m^2/g, and for bentonite, 250–500 m^2/g, which determines the higher activity of the latter and the possibility of reducing its content in the composition while maintaining the required properties (Kulikov et al., 2024; Kukuy et al., 2005; Gulyaev et al., 1987).

Research materials and methods. The objects of the study were fly ash from TPP 2 in Almaty and bentonite from a deposit in the Republic of Kazakhstan. The physico-chemical properties of fly ash were determined using an Axios PANalytical X-ray fluorescence spectrometer (the Netherlands) and a D8 ADVANCE diffractometer from Bruker Elemental GmbH (Germany). Thermal analysis was performed on a STA 449 F3 Jupiter "NETZSCH" derivatograph (Germany) in an inert atmosphere. The morphology was studied using a JEOL JXA-8230 microprobe analyzer (Japan) and an Olympus BX-51 optical polarization microscope (Japan).

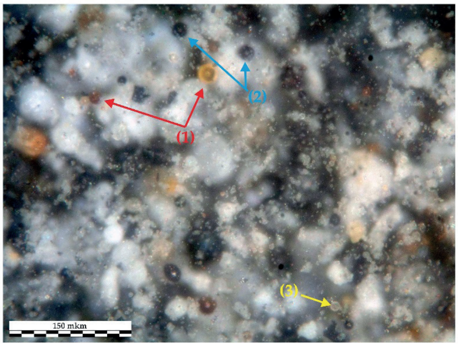
Three samples of fly ash from the dry storage ash dumps of the Thermal Power Plant 2 in the Alatau district of Almaty were analyzed. The samples were averaged and reduced through quartering.

Wood flour (WF) with a dispersity of not more than 0.4 mm, produced on a hammering machine from sawdust, furniture production waste, was used as a wood filler.

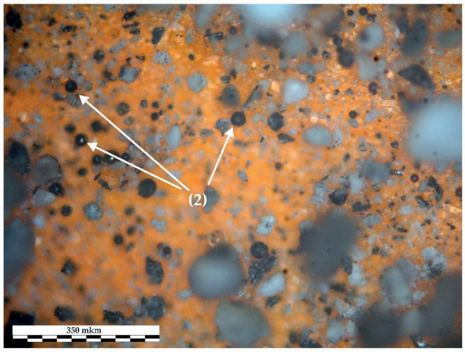
Results and discussion. The fly ash samples studied in the work showed the value of the specific effective activity of natural radionuclides less than 370 Bq/kg. It corresponds to the first class and allows the use of these materials for all types of construction.

Morphologically, the fly ash is a finely dispersed material consisting of sand and glassy particles with different composition and structure. The original color of the ash is light gray.

Figure 1 (a, b), Figure 2 (b) presents the fly ash results of microscopic studies owhere microsphere-formed particles gas-filled, hematite, silicate spheres.



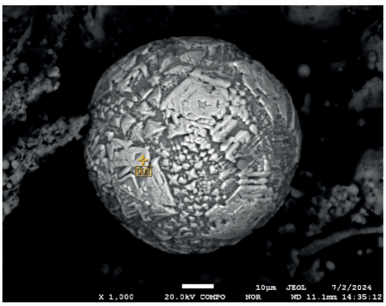
a)



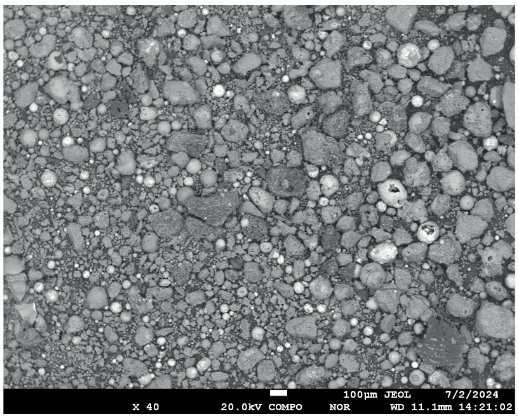
b)

Figure 1 – Micrograph of fly ash at TPP 2, Almaty. Magnification x 300
1) gas-filled spheres; 2) hematite spheres; 3) silicate spheres

Besides, spheroidal particles of magnetite (Fe_3O_4) mixed with hematite (Fe_2O_3) and spheres of mixed composition are found in the fly ash composition. It is confirmed by X-ray phase analysis. Figure 2 (a) shows a micrograph of spherical particles having a complex composition consisting of an aluminosilicate base coated with heavy metals.



Chemical formula	ms%	mol%	Sigma	Net	K ratio	Line
O	45.18	72.79	0.17	4127739	0.4537851	K
Al	2.13	2.03	0.20	413207	0.0122870	K
Si	1.75	1.60	0.19	396528	0.0128960	K
Ca*	0.31	0.20	0.23	72575	0.0041199	K
Fe	50.64	23.37	0.55	5177345	0.5822999	K
Total	100.00	100.00				



a) a particle with magnification of 1000; b) particles with magnification of 40;

Figure 2 – Scanning microscope of TPP 2 fly ash

According to the analysis, oxygen is present in the shell of the sphere - 41.83%; iron -17.22%; calcium – 1.32%; copper – 1%. The information correlates with the phase analysis diffraction data.

X-ray phase analysis of the fly ash showed angle spectra and diffraction intensities characteristic of such minerals as sillimanite AI_2SiO_5, mullite Al_4SiO_8, and quartz SiO_2, with the presence of hematite (Fe_2O_3). The data are presented in Table 1.

Table 1 – Results of fly ash phase analysis at TPP 2 in Almaty

No.	Compound Name	Formula	S-Q
1	Sillimanit	Al_2SiO_5	32.5
2	Mullite	Al_4SiO_8	27.2
3	Hedenbergite	$CaFeSi_2O_6$	12.4
4	Quartz low	SiO_2	8.7
5	Hematit	Fe_2O_3	6.7
6	Other		12.5

The FA contain an amorphous substance consisting of vitreous spheres. It appears as a halo on X-ray spectra. The crystalline phase consists mainly of silicates, which make up 80,8% in total.

Figure 3 shows a comparison of the dispersion of fly ash and wood flour. The particle size of FA ranges from 90 to 300 micrometers, with no ultrafine or dust-like particles present in the filler. The average particle size (DAV) is 182.0 micrometers; the 90% particle size class (D90) is 281 micrometers. The maximum particle size (Dmax), i.e., 300 micrometers, is 20.1%. The minimum particle size (Dmin), i.e. 40 µm, is 0.5%. Less than 1% of large particles were removed during sieve analysis.

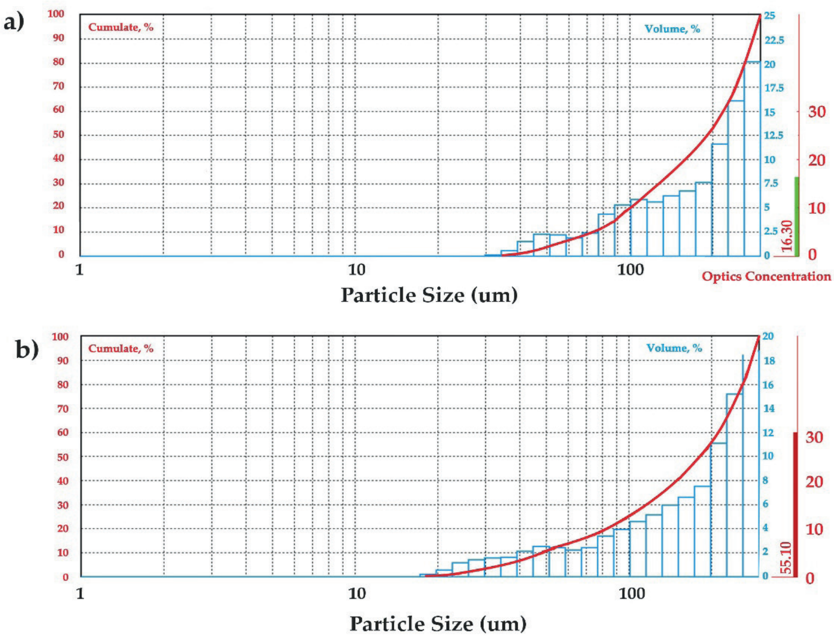


Figure 3 – Granulometric analysis of dispersed filler
a) coal fly ash; b) wood flour

For WF, particle size DAV is 172.68 μm; 90% class D90 is 279.68 μm. Dmax, i.e. 300 μm, is 18.755%. particles Dmin, i.e. 20 μm, is 0.2%.

Thermal studies of FA were conducted using two methods: calcination and thermogravimetric analysis. Crucibles with samples were heated to a constant weight at a temperature of 1000 ± 50 °C to determine the completeness of coal combustion. The average weight loss was 0.9%.

DTA analysis was performed by heating the sample in a high-purity argon atmosphere at a heating rate of 50 °C/min to 2500 °C. °C/min. Figure 4 shows that no effects were detected on the DTG curve, while the TG curve shows that the rate of mass loss at 20–2500 °C is constant. The weight change after heating to 2500 °C was 0.2%. The change in mass at 2000 °C was 0.12%.

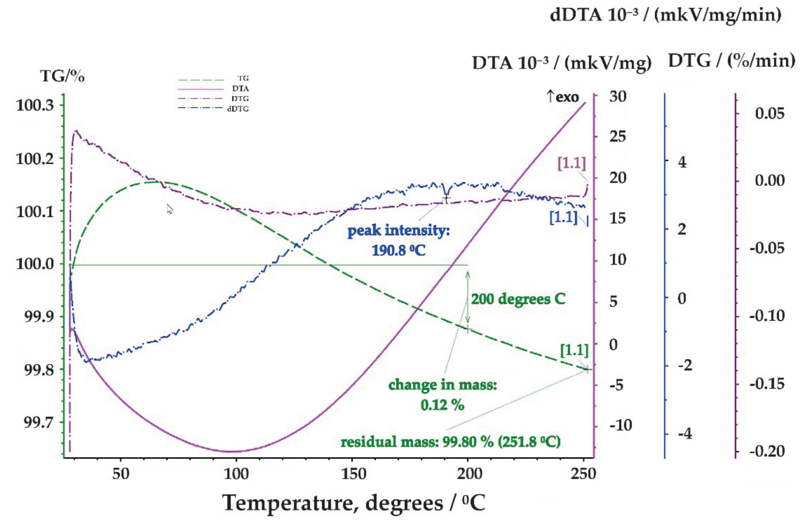


Figure 4 – Differential thermal analysis of fly ash at TPP 2 in Almaty

Accordingly, the composition of the FA will remain constant when used in heating processes.

Study of bentonite. Sample of bentonite from the Kazakhstan deposit has a finely dispersed structure, a light color, with a yellowish tint.

Bentonite consists mainly of oxygen O - 57.3%; silicon Si – 27.5%, and Ca content is 1.16%, Na+K is 1.94% under the X-ray fluorescence analysis, as presented in Table 2.

Table 2 – Elemental composition of bentonite samples

Compound formula	Concentration	Compound formula	Concentration	Compound formula	Concentration
Si	27.561	S	0.070	Ti	0.704
O	57.358	Cl	0.224	Mn	0.030
Na	1.647	K	0.298	Fe	2.928

Mg	1.538	Ca	1.166	Zn	0.005
Al	6.392	P	0.069	Zr	0.007

Bentonite clay samples were subjected to a thermal modification process. Three samples of bentonite weighted 40 g each were taken for this purpose and calcined in a muffle furnace, with a holding time of 40 minutes, at 200, 500 and 700 ^{0}C, respectively. Calcination at the temperature of more than 500 ^{0}C removes water, and the use of calcined and modified bentonite in composite materials increases the temperature of their processing. The removal of water and the formation of anhydrous clays takes place at 500-700 ^{0}C.

It can be seen based on the X-ray phase analysis conducted for bentonite clay (Figure 5) that the following minerals are present in the sample - montmorillonite ($Al_2(OH)_2{\cdot}(Si_4O_{10}){\cdot}mH_2O$); Al_2O_3; quartz (SiO_2) and hematite (Fe_2O_3). $[(KH_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2{\cdot}(H_2O)]$, but there is considerable ion (isomorphic) substitution. The content of illite can be assumed in this sample, and it is a non-swelling type of bentonite.

A decrease in the intensity of hydrate silicate lines is observed in the spectrum of the thermally modified sample at 700 ^{0}C, and the spectrum of the diffraction angle of titanium oxide appears. The amount of crystalline phase in a sample of modified bentonite is reduced to 46% (by 6%).

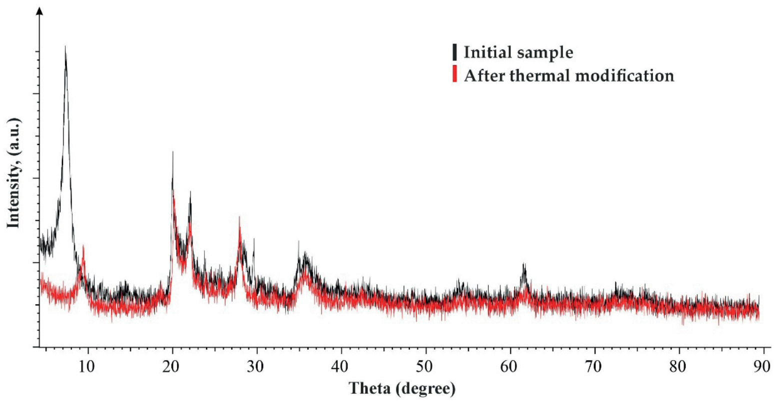


Figure 5 - XR spectrums of raw and modified at 700 ^{0}C bentonite

Quartz SiO_2 and alumina Al_2O_3 dominate in the initial bentonite sample according to the phase analysis results (Table 3), These oxides are rock-forming components typical of montmorillonite-based clays.

Table 3 – Phase analysis results for the original bentonite sample

Phase composition	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O+K_2O	SO_4^{2-}	TiO_2
Content, %	61.0	18.02	2.01	2.5	9.3	2.64	2.6	2.1

Titanium and iron oxides with the TiO_2 and Fe_2O_3 formulas are coloring oxides, with an average content of 1 to 5%. Na_2O, CaO and MgO are part of both the clay itself and impurities. The sodium, magnesium, and calcium cations in bentonites play the role of exchangeable cations, and the content of each oxide can range from fractions of a percent to 2–3%.

Figure 6 shows a decrease in the average and minimum particle size in a bentonite sample modified at 700 ^{0}C.

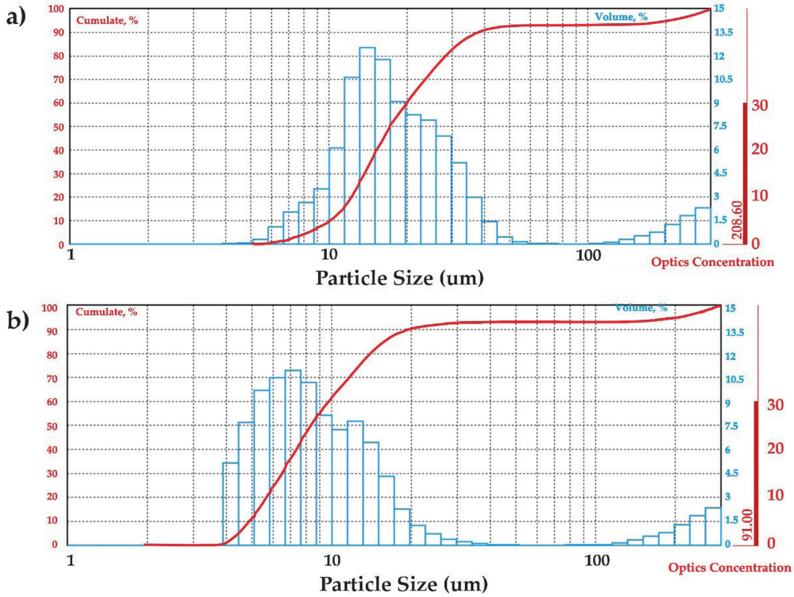


Figure 6 – Granulometric analysis of bentonite:
a) original sample; b) a sample modified at 700 ^{0}C

The average DAV particle size is 33.6 µm in the original bentonite sample; 90% particle size class D90 is 37.59 µm. The maximum particle size D_{max} –300 µm is 2.3 %; particle size D_{min} – 6.6 µm ~ 1.1 %.,

Thermal modification at 700 ^{0}C had an effect on the dispersion composition of the sample. The DAV size decreased to -25.321 µm; particle size class D90 decreased to -19.75 µm, D_{max} is 300 µm, content is 2.3 %; Dmin decreased to 4.45 µm, and the content of particles with D_{min} increased to 5.1%.

Samples for the study were obtained by extrusion, the composition included 48% polymer components, i.e. low-density polyethylene (HDPE) and 52% fillers made of WF and chalk, ash, bentonite and technological additives. WF was classified by size, dried at 70 ^{0}C, then mixed with fly ash, dried to almost zero humidity, treated with thermally modified and dried bentonite, then the mixture was used to obtain a wood-polymer composite material.

Samples of WPC materials were tested depending on changes in the composition in order to determine their physical, mechanical and strength properties

Specimens had sizes of 210×16×5 mm for bending and hardness tests, and the sizes of 70×16×5 mm for water absorption tests. The bending strength was measured under ISO 178 standards and recommendations by three-point loading at a speed of 0.5 mm/min. The hardness of the specimens according to Brinell was determined according to ISO 2039-1 by pressing a steel ball with a diameter of 5 mm into the surface of the test specimen with a force of 5 kgf. 15 seconds after the load was applied, the depth of the impression was measured. The water absorption under ISO 62 was measured by immersion in distilled water for 24 hours at t 23 ^{0}C. After holding in water, the sample was dried with filter paper, the geometric dimensions were measured and weighed.

Testing of samples of WPC materials depending on the change in the composition, including 20% of fly ash and 5% of bentonite modified at 200%; 500 and 700 ^{0}C (hereinafter bentonite 200, bentonite 500, bentonite 700) are presented in Table 4.

Table 4 – Strength characteristics of WPC materials depending on the content of bentonite

No.	Name	Fly ash %	Bentonite, % modification	Bending strength MPa	Max deformation %	Brinell hardness HB	Water absorption %
1	WPC No. 1	20%	5%, Bentonite 200	14.28	1.6/4.82	7.71	0.75
2	WPC No. 2	20%	5%, Bentonite 500	14.80	2.1/6.49 mm	7.77	0.45
3	WPC No. 3	20%	5%, Bentonite 700	20.90	2.26/4.57 mm	12.37	0.45

It has been established that the bending strength of a specimen with the addition of bentonite 700, in comparison with a specimen containing bentonite 200, increases by 32%, and the hardness also increases by 60%, from 7.71 to 12.37 HB. Water absorption decreases to 40% in bentonite 500 and 700 samples, and is 0.45%.

Figure 7 shows plots of sample deformation versus stress for samples with bentonite content: 200; 500; 700 respectively.

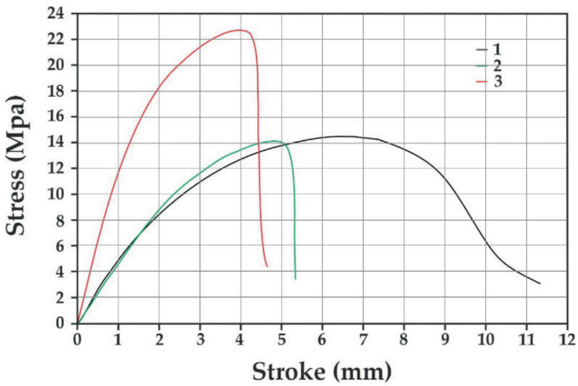


Figure 7 – Dependence of maximum stress and deformation of thermally modified bentonite specimens.
1 - t ^{0}C: 200; 2 - t ^{0}C: 500; 3 - t ^{0}C: 700

It can be assumed based on the values of the maximum stress and deformation and the shape of the graphs that the hardness of the specimen with composition 3 with bentonite 700 increases, the smooth stroke of the stress-stroke curve of specimen 1 suggests the viscosity of the material.

Testing of WPC material samples depending on changes in the characteristics of the polymer matrix based on primary HDPE and secondary HDPE obtained by extrusion and granulation of secondary raw materials from solid waste. The composition included: 20% of the fly ash; 5% bentonite 700; wood flour and additives. The results are presented in Table 5.

Table 5 – Strength characteristics of WPC materials depending on the polymer matrix.

No.	Name	Fly ash %	Polymer matrix	Bending strength MPa	Max deformation %	Brinell hardness HB	Water absorption %
1	WPC No. 4	20%	48% HDPE primary	22.40	2.26/6.57 mm	7.70	0.75
2	WPC No. 5	20%	48%, secondary HDPE from solid waste	13.20	1.1/3.86 mm	9.77	0.45
3	WPC No. 3	20%	48%, HDPE secondary	20.90	2.26/4.57 mm	8.47	0.45

According to the test results, the composite material based on a matrix made of recycled HDPE from solid waste has lower bending strength, bending strength up to 13.2 MPa, high hardness of 9.77 HB and low water absorption - 0.45%.

The bending strength of a sample made of primary plastic increases to 22.4 MPa, the Brinell hardness is 7.70 HB, the bending strength of a sample based on secondary HDPE is slightly lower, 20.90 MPa, and the Brinell hardness is higher, up to 8.47. The moisture capacity of the sample based on matrices from secondary HDPE and HDPE from solid waste is 0.45%, which is 40% lower than the moisture capacity of the sample from primary HDPE – 0.75%.

Tests of WPC material samples depending on the change in the bentonite content 700 in %: 2; 5; 8; 30 respectively.

The WPC samples are made of a composition based on a polymer matrix of secondary HDPE, and a filler of wood flour, 20% fly ash with the addition of bentonite 700. Results are presented in Table 6.

Table 6 – Strength characteristics of WPC materials depending on the content of thermally modified bentonite

No.	Sample	Bentonite content %	Bending strength MPa	Brinell Hardness HB	Water absorption, %
1	WPC No. 6	2	14.50	8.70	0.46
2	WPC No. 3	5	20.90	8.47	0.45

3	WPC No. 7	8	19.80	8.50	0.40
4	WPC No. 8	30	14.25	9.0	0.75

As it can be seen from the test results, samples from compositions with a bentonite content of 2, 5, 8 % have low water absorption, from 0.40 to 0.46 %, and the moisture capacity of the samples decreases with an increase in the content of bentonite. So, the moisture absorption parameters are 0.40% in a composition containing 8 % bentonite. When the bentonite content increases up to 30% water absorption increases to 0.75%. It can be explained by the moisture capacity of bentonite, to which water has access through the pores. Besides, an increase in the hardness of the sample up to 9 HB is observed with an increase in bentonite content up to 30%. The bending strength increases for a specimen with a content of 5% to 20.9 MPa, a further increase in the bentonite content to 8% contributed to a decrease in the bending strength to 19.8 MPa. The bending strength was reduced to 1.25 Mpa for a specimen with a bentonite content of 30%.-

Testing of WPC material samples depending on the change in the fly ash content. Samples with a change in the fly ash content in %: 0; 5; 20 and 30, made based on a composition of polymer matrix of the secondary HDPE, filler of wood flour and bentonite 700 in the amount of 5% were tested to study the possibility of using the fly ash as a filler for WPC. The results of the sample studies are shown in Table 7.

Table 7 – Strength characteristics of WPC materials depending on the fly ash content

No.	Sample	Fly ash content %	Bending strength. MPa	Brinell Hardness HB	Water absorption, %
1	WPC 0	0	18.25	6.75	0.75
2	WPC 9	5	18.80	8.47	0.45
3	WPC 3	20	20.90	8.47	0.45
4	WPC 10	30	14.80	6.45	0.40

The introduction of 5-20% of the fly ash into the composition contributes to the increase in the strength properties of the composite material, the bending strength increases up to 14.5%, the hardness of the samples increases up to 10%, while the increase in the content of the fly ash in the composition to 30% reduces the tensile strength and hardness of the composition. The water absorption of the WPC material decreases with the increase of the fly ash in the composition.

Fly ash meets such requirements for fillers as dispersion, moisture capacity, consistency of composition and mass under thermal action, as well as chemical inertia, which are necessary properties for extrusion, the data are consistent with studies (Kijo-Kleczkowska et al., 2024:130168). The decrease in the strength of the sample and the increase in water absorption with an increase in the bentonite content in the composition up to 30% can be explained by the agglomeration of particles and the absorption of water by bentonite. (Tables 6, 7). These data are confirmed by bentonite modification studies. They show a significant difference in dispersibility and particle distribution in the elastomeric matrix compared to unmodified ones, and the performance properties of the compositions are 1.6–1.8 times higher than those of composites filled with unmodified fillers (Ibadullayev et al., 2021:05006). Bentonite is modified chemically or thermally to improve dispersibility. The problem of bentonite clumping in the polymer can be solved by adding large particles to the polymer matrix simultaneously with bentonite (Puchkova et al., 2012:46).

Filling the material with fly ash up to 20% contributes to an increase in the strength, hardness of the sample with a decrease in water absorption, and the strength and hardness of the sample decreases with a further increase in the content of fly ash up to 30%.

Conclusion The conducted studies showed that the fly ash from Almaty TPP-2 is a homogeneous aluminosilicate material consisting mainly of spherical glassy particles and crystalline phases of Sillimanite, Mullite, and Quartz. Its low loss on ignition and stable mineral composition make it a suitable functional filler for polymer composite materials.

Thermal modification of bentonite at 700 °C led to dehydration, partial amorphization, and a 25 % reduction in the mean particle size, accompanied by a fivefold increase in the fine fraction. These structural changes significantly improved the dispersion capacity of bentonite and its interaction with the polymer matrix.

The introduction of 20 % fly ash and 5 % thermally modified bentonite into the composite formulation increased flexural strength by 32 %, hardness by 60 %, and reduced water absorption to 0.45 %. This demonstrates a synergistic reinforcing effect of fly ash and thermally modified bentonite in the WPC structure.

The scientific novelty of the research lies in establishing the correlation between the thermal modification temperature of bentonite, the change in dispersion of its mineral phase, and their combined influence on the mechanical properties and interfacial adhesion of wood–polymer composites.

The results can be used to develop cost-effective, environmentally friendly composite materials based on locally available industrial waste.

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